An Adaptive Hand exoskeleton for Teleoperation System

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Research Article

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An Adaptive Hand Exoskeleton for Teleoperation System

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Abstract

Teleoperation can assist humans in completing various complex tasks in inaccessible or high-risk environments. Adequate adaptability should be available to enable the exoskeleton master hand to capture the motion of human fingers and reproduce the contacting force between the slave hand and its object. This paper presents a novel finger exoskeleton based on the cascading four-link closed-loop kinematic chain. Each finger has an independent kinematic chain, and the angle sensor is employed to measure the finger movement including the flexion/extension and the adduction/abduction angle. The servo motor controls the tension of the tendon to transmit the contacting force to the fingers in real time. An adaptive hand exoskeleton is consequently developed based on the finger exoskeleton. The experiment results show that the adaptive hand exoskeleton could be worn without any mechanical constraints, and the slave hand could follow the motions of each human finger. The accuracy and the real-time capability of the contacting force reproduction were validated to be superior. The designed adaptive hand exoskeleton could be employed as the master hand to remotely control the humanoid five-fingered dexterous slave hand, thus, enabling the teleoperation system to complete complex dexterous manipulation tasks.

Keywords: Hand exoskeleton, Humanoid dexterous hand, Teleoperation, Motion capture, Force-reproduction

1 Introduction

Teleoperation exploits human knowledge and experience of remote control, which reduces the requirements of robots for learning, modeling, and controlling. Thus, it is widely applied to surgical robots, drones, unmanned vehicles, and other fields [1]. For high-risk environments with complex manipulating scenarios, such as bomb demolition, dangerous goods disposal, oil, and gas valve operation, it is necessary to have a humanoid five-fingered dexterous slave hand with flexible operational capabilities such as screwing, pushing, pulling, and pressing [2]. Therefore, the exoskeleton master hand is expected to be worn by humans to acquire agile motion.

As one of the core components of the master-slave teleoperation system, the exoskeleton master hand is required to map the motion of each finger to the bionic five-fingered dexterous slave hand and transmit the interaction force between the hand and its object to the human hand [3][4]. In general, the following three problems should be considered in the design of the exoskeleton master hand. First, the motion of fingers should not be mechanically constrained, even for different-sized hands. Second, there tends to be coupling motion between the human finger and its joints, which sets the challenge of accurately capturing the angle of each joint. Third, it should reproduce the interactive force from the slave hand in real time.

Amirpour E et al. [6] proposed a two-fingered hand exoskeleton HEXON. Each finger has 3 DoFs (degrees of freedom), and the end-to-end single-point connection forms a motion closed chain, which can remotely operate the mechanical gripper to complete target grasping. Because the captured human motion information was limited to the thumb and index finger, the exoskeleton cannot cover the entire

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hand. So, it did not have the above-mentioned multi-task operation capability. Park Y et al. [7][8] proposed a three-fingered hand exoskeleton WeHAPTIC for manipulating objects in virtual reality applications. The exoskeleton consisted of two rods connecting the fingertip and the opisthenar to form a closed-loop kinematic chain. Based on the fingertip posture estimation algorithm, the kinematic angle of the finger joint was solved. For different users, the estimation algorithm needed to be calibrated in advance. This undoubtedly increased the complexity of the measurement operation. The acquisition of finger motion by the exoskeleton relied on a complex kinematic model, which reduced the accuracy of motion capture. The University of Pisa developed a hand exoskeleton ExoSense [9] for tracking human hand operations. Each finger exoskeleton integrated a sensor to obtain the position of the contact object. The system also needed calibration before using. Furthermore, the exoskeleton only has a tactile detection function and cannot achieve force-sensing reproduction. The force feedback exoskeleton Dexmo [10][11] developed by Dexta Company could feedback the interaction force from the exoskeleton and its object through a motor with a high gear ratio. However, when the slave hand did not touch the object, it is difficult to simulate the free movement of fingers at low impedance because of the large transmission ratio, which limits the performance of the human hand.

In addition to the above-mentioned commonly used DC motor [14], pneumatic artificial muscle (PAM) antagonism [15], and magnetorheological fluid damper [16] are also employed as actuating techniques for the hand exoskeleton. Yuki Zheng et al. [17] proposed a low-impedance force feedback data glove based on pneumatic artificial muscles, which satisfied the low-impedance movement of the master hand in free space. Although the pneumatic artificial muscles offer low stiffness, there is a delay in force perception reproduction.

To realize the dexterous operation of the humanoid five-fingered dexterous slave hand, this paper presents a novel closed chain cascade configuration of finger joints for the adaptive hand exoskeleton. Each finger has an independent kinematic chain, and the angle sensor is employed to measure the finger movement including the flexion/extension and the adduction/abduction angle. The tension of the tendon is controlled by a servo motor to transmit the interaction force to the fingers in real time.

The remainder of this paper is organized as follows. Section 2 provides a brief description of the closed chain cascade structure and the adaptive hand exoskeleton. Section 3 presents the motion capture model and the master-slave control strategy. Section 4 describes the performance verification experiment. Section 5 analyzes the experimental results, followed by the discussion in section 6. Finally, section 7 draws the conclusion.

2 Configuration mechanism

The schematic diagram of the proposed finger exoskeleton is shown in Figure 1(a). Each finger joint possesses an independent four-link closed-loop kinematic chain. Taking the PIP joint as an example, the geometric relationship of the closed-loop kinematic chain is shown in Figure 1(b). The O_{PIP} represents the rotation center of the PIP joint, and the rotation center of the flexion-extension angle sensor is coaxial with the hinge D. Different from the DIP and PIP joints, as shown in Figure 1(c), the MCP joint has 2 DoFs of flexion/extension, and adduction/abduction movements (side swing movements). Thus, an angle sensor is added at the base of the exoskeleton to detect the side-swing movements. Figure 1(d) shows the geometric relationship of the closed-loop kinematic chain of the MCP joint. The O_{MCP} represents the rotating center, and the roll angle sensor is coaxial with the rotating center of the adduction/abduction motion. The kinematic closed chains of the DIP, PIP, and MCP joint are cascaded to form a finger exoskeleton, which can adapt to different users without restricting human hand motion. Similarly, the IP, MCP, and CMC joints of the thumb have the same four-link closed-loop kinematic chain structure as the DIP, PIP, and MCP joints of the index finger.

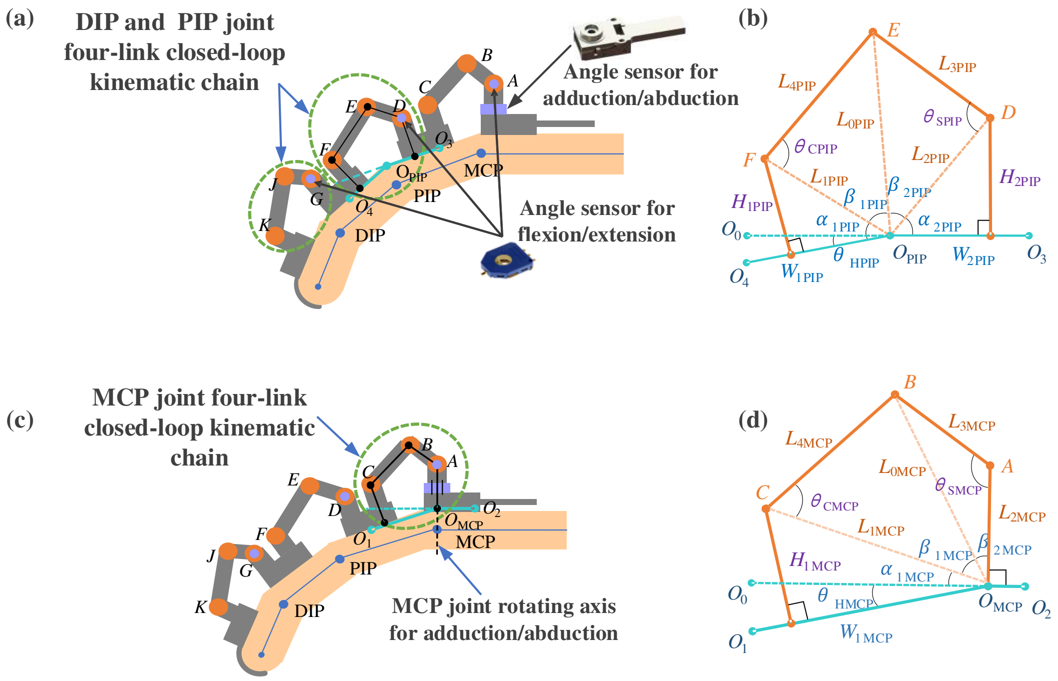

Figure 1. Schematic diagram of the finger exoskeleton. (a) The closed chain structure of the finger exoskeleton. (b) The mechanism of the PIP joint. (c) The closed chain structure of the MCP joint. (d) The mechanism of the MCP joint.

We used the servo motor as the driver source to realize the force reproduction for the exoskeleton master hand. Figure 2 shows the integrated units of the force reproduction system. The servo motor and winding tiller constitute the driving unit. The tendon, constraint holes, and constraint slots constitute the transmission unit. The spring, touch force sensor, and various components constituted the detection unit. To ensure the independence of each finger joint, the kinematic closed chains were connected in series by a tendon. Taking the contacting force of the slave hand as the input reference, the servo motor drove the winding tiller to change the tendon length, further, restraining the motion of the exoskeleton and transmitting the force to the finger. The detection unit converted the change of tendon length into tendon tension, which was detected by the FSS1500NST touch force sensor (Honeywell Inc, North Carolina, US). The spring provided the pre-tightening force for the tendon, to improve the real-time responsiveness of the detection unit.

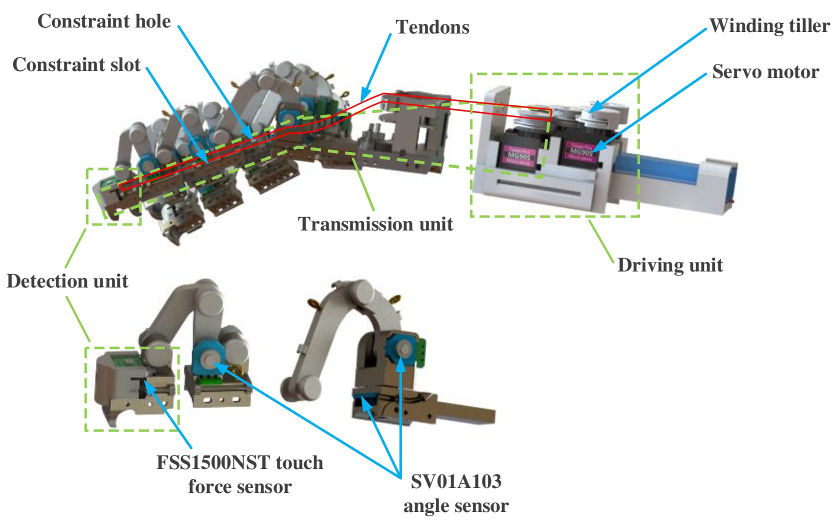

Figure 2. Force-reproduction system.

Based on the above-mentioned finger exoskeleton configuration and force reproduction system, an adaptive hand exoskeleton is proposed. The physical prototype is shown in Figure 3(a). The exoskeleton is attached to the elastic fiber gloves with an arc-shaped restraint ring. The total weight is below 300g.

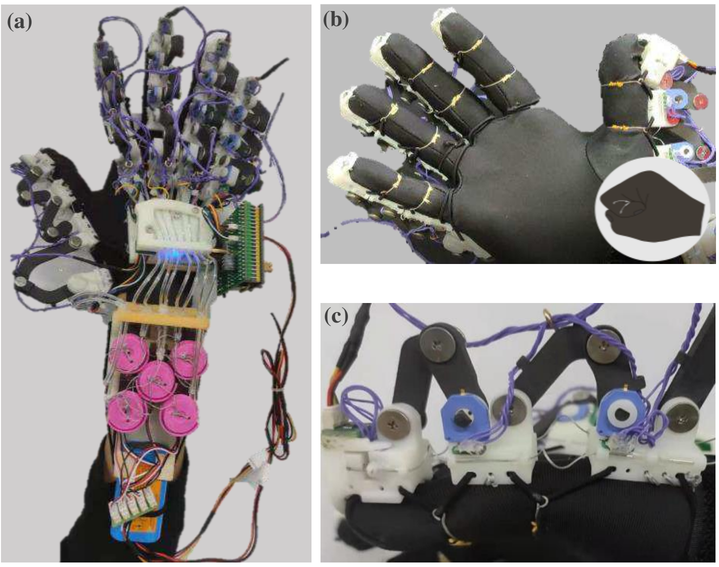

Figure 3. Adaptive hand exoskeleton. (a) The prototype of the adaptive hand exoskeleton. (b) Worn on the hand. (c) Worn on the finger.

3 Mathematic model and control

3.1 Joint flexion/extension angle

According to the geometric relationship of the closed-loop kinematic chain of each finger joint in Section 2, the sensor for adduction/abduction movement is coaxial with the joint rotation center, and the angle of this movement can be directly sampled from the sensor. Still, the flexion/extension movement angle needs to be converted and solved by the geometric model.

As shown in Figures 1(c) and (d), in the PIP joint, for example, the joint angle θ_{HPIP} can be expressed as:

$$\theta_{\mathrm{HPIP}} = \alpha_{1\mathrm{PIP}} + \alpha_{2\mathrm{PIP}} + \beta_{1\mathrm{PIP}} + \beta_{2\mathrm{PIP}} - \pi \tag{1}$$

$$\begin{aligned} &\alpha_{1\mathrm{PIP}} = \arctan\left(\frac{H_{1\mathrm{PIP}}}{W_{1\mathrm{PIP}}}\right), \alpha_{2\mathrm{PIP}} = \arctan\left(\frac{H_{2\mathrm{PIP}}}{W_{2\mathrm{PIP}}}\right), \\ &\beta_{1\mathrm{PIP}} = \arcsin\left(\frac{L_{4\mathrm{PIP}} \sin\theta_{\mathrm{CPIP}}}{L_{0\mathrm{PIP}}}\right), \beta_{2\mathrm{PIP}} = \arcsin\left(\frac{L_{3\mathrm{PIP}} \sin\theta_{\mathrm{SPIP}}}{L_{0\mathrm{PIP}}}\right) \end{aligned} \tag{2}$$

where θ_{HPIP} is the joint angle; θ_{SPIP} is the desired measurement angle from the angle sensor; $H_{1\mathrm{PIP}}$, $H_{2\mathrm{PIP}}$, $W_{1\mathrm{PIP}}$, $W_{2\mathrm{PIP}}$, $L_{3\mathrm{PIP}}$, $L_{4\mathrm{PIP}}$ are the lengths of the rods to be measured; θ_{CPIP}, $L_{0\mathrm{PIP}}$ can be obtained by the cosine theorem.

Furthermore, the PIP joint angle θ_{HPIP} can be expressed as a function of the angle θ_{SPIP}.

$$\begin{aligned} \theta_{\mathrm{HPIP}} = &\arctan\left(\frac{H_{1\mathrm{PIP}}}{W_{1\mathrm{PIP}}}\right) + \arctan\left(\frac{H_{2\mathrm{PIP}}}{W_{2\mathrm{PIP}}}\right) - \pi + \arcsin\left(\frac{L_{4\mathrm{PIP}} \sin\theta_{\mathrm{CPIP}}}{L_{0\mathrm{PIP}}}\right) \\ &+ \arcsin\left(\frac{L_{3\mathrm{PIP}} \sin\left(\theta_{\mathrm{SPIP}} - \theta_{\mathrm{dPIP}}\right)}{L_{0\mathrm{PIP}}}\right) \end{aligned} \tag{3}$$

Similarly, for the MCP joint, the joint angle θ_{HMCP} of its flexion/extension motion can be expressed as:

$$\begin{aligned}\theta_{\mathrm{HMCP}} &= \alpha_{1\mathrm{MCP}} + \beta_{1\mathrm{MCP}} + \beta_{2\mathrm{MCP}} - \frac{\pi}{2} = \arctan\left(\frac{H_{1\mathrm{MCP}}}{W_{1\mathrm{MCP}}}\right) - \frac{\pi}{2} \\ &+ \arcsin\left(\frac{L_{4\mathrm{MCP}}\sin\theta_{\mathrm{CMCP}}}{L_{0\mathrm{MCP}}}\right) + \arcsin\left(\frac{L_{3\mathrm{MCP}}\sin\left(\theta_{\mathrm{SMCP}} - \theta_{\mathrm{dMCP}}\right)}{L_{0\mathrm{MCP}}}\right)\end{aligned} \tag{4}$$

The θ_{dPIP} and θ_{dMCP} in equations (3) and (4) are the errors between the actual measurement angle and the desired measurement angle of the PIP and MCP joint angle sensors, respectively, which need to be compensated when calculating the joint angle.

3.2 Master-slave mapping

To ensure that the slave hand can follow the movement of the master hand in the teleoperation, it is necessary to establish an appropriate mapping relationship between the corresponding joints of the master hand and the slave hand. The mapping relationship between the angle change value $\Delta\theta_{\mathrm{H}}$ of the master hand joint and the angle change value $\Delta\theta_{\mathrm{R}}$ of the slave hand joint is:

$$\Delta\theta_{\mathrm{R}} = k\Delta\theta_{\mathrm{H}} \tag{6}$$

where k is the mapping coefficient.

The larger the k is, the more sensitive the slave hand will be. On the contrary, the smaller the k is, the more accurate the slave hand will be, which is more conducive to dexterous manipulations.

The adaptive exoskeleton master hand has 20 DoFs. If a humanoid five-fingered dexterous hand with 20 DoFs is employed as the slave hand, the mapping relationship is as follows:

$$\begin{pmatrix}\Delta\theta_{\mathrm{R}1} \\ \vdots \\ \Delta\theta_{\mathrm{R}20}\end{pmatrix} = \begin{pmatrix}k_1 & & 0 \\ & \ddots & \\ 0 & & k_{20}\end{pmatrix}_{20\times 20}\begin{pmatrix}\Delta\theta_{\mathrm{H}1} \\ \vdots \\ \Delta\theta_{\mathrm{H}20}\end{pmatrix} \tag{7}$$

3.3 Master-slave control strategy

Based on the force-position double-loop control method, a master-slave control strategy is designed. The master side is the proposed adaptive exoskeleton master hand, the slave side is the humanoid five-fingered dexterous slave hand with the same number of DoFs. The position control loop realizes the following movement of the slave hand, and the force control loop realizes the force reproduction of the master hand. The control strategy is shown in Figure 4.

When the slave hand moves in free space and has no force feedback, the reference input of the master hand is the preset initial tension value provided by the spring. When the slave hand interacts with its object, the contacting force is the reference input for the master hand. $\Delta\theta_{\mathrm{H}}$ is the angle variation of the master hand joint. $\Delta\theta_{\mathrm{R}}$ is the angle variation of the slave hand joint. In Figure 4, k is the master-slave mapping coefficient. F_{e} is the pressure value of the fingertip of the slave hand. k_{s} is the tension conversion coefficient. F_{p} is the initial tension value of the tendon. F_{m} denotes the tension value for the master hand.

4 Experiments

4.1 Motion tests

Before the teleoperation experiment, the subject wore the developed adaptive exoskeleton prototype to perform the motion test of flexion/extension, and adduction/abduction of each finger joint, as shown in Figure 5.

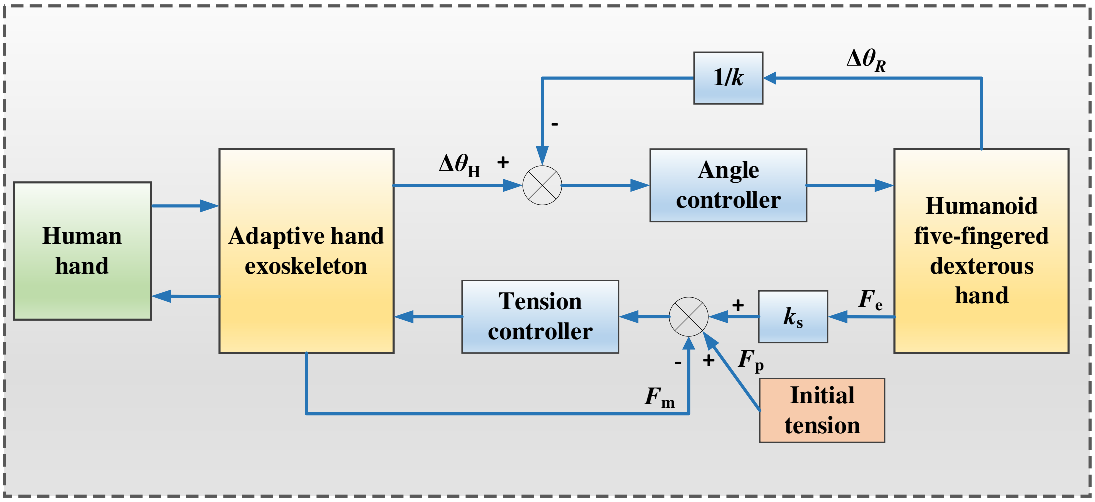

Figure 4. Diagram of the master-slave control strategy.

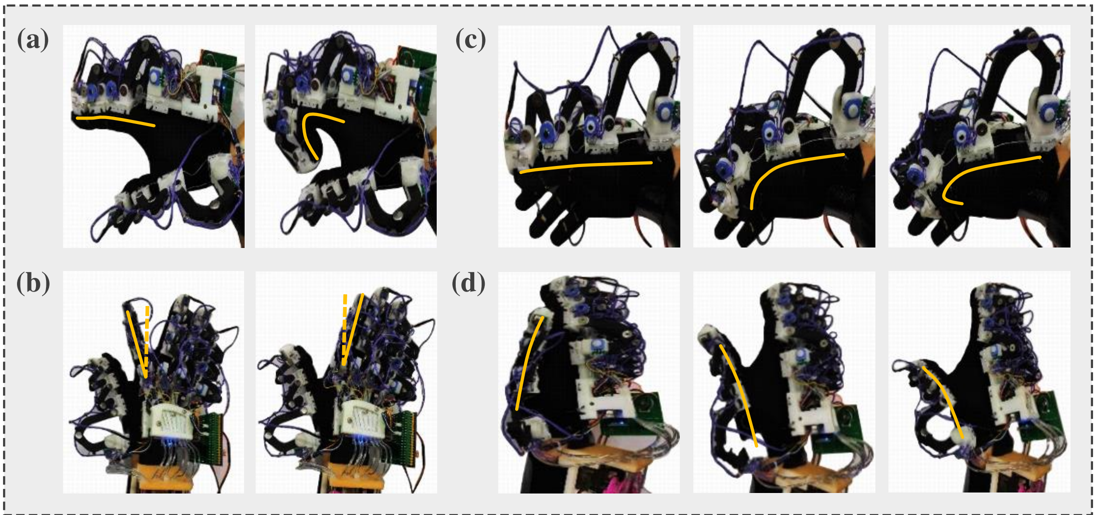

Figure 5. The motion tests of the hand exoskeleton. (a) Four fingers flexion/extension. (b) Four fingers adduction/abduction. (c) Thumb flexion/extension. (d) thumb adduction/abduction.

It can be observed from Figures 5(a) and (b) that during the movement of the four fingers, the exoskeleton was always attached to the finger, with neither movement interference between the adjacent finger exoskeletons, nor mechanical constraints. The movement process of the thumb is more complicated. As shown in Figures 5(c) and (d), when the thumb CMC joint performed flexion and extension, significant adduction and abduction happened. In the CMC joint, adduction/abduction was accompanied by flexion/extension, and the two DoFs were coupled. However, the exoskeleton can still be admirably adapted to the thumb joints.

4.2 Grasping tests

The grasping test was further conducted based on the Feix grasping classification method [23][24]. As shown in Figure 6, the grasping ability of the exoskeleton after wearing was verified through various actions such as strong grasping, intermediate grasping, and precise grasping. The results show that the exoskeleton master hand has good adaptability.

4.3 Teleoperating tests

The teleoperating experimental platform is shown in Figure 7(a). The fully driven uncoupled humanoid five-fingered dexterous hand (FDBM-Hand) [18] was employed as the slave hand, as shown in Figure 7(b). The FDBM-Hand is composed of five modular fingers and a palm, which has the same number of DoFs as the master hand exoskeleton. Each finger joint is independently controlled through PAM.

Based on the above-mentioned teleoperation experimental system, the following experiments were conducted.

(1) Motion capture experiment

Taking the index finger of the master hand exoskeleton as an example, its DIP, PIP, and MCP joints bent to 30° and 60° in turn. Multiple experiments were conducted to demonstrate repeatability.

(2) Tension control experiment

To improve the capability of the response of the master hand exoskeleton to the contacting force instantaneously, an initial tension of the tendon was preset. Verifying the control effect of the tension of the tendon is a necessary process to determine that the adaptive hand exoskeleton can accurately reproduce the slave hand contacting force information. In this experiment, the flexion/extension of the index finger was taken as an example, and the tension of the tendon was controlled during the dynamic change of the joint angle.

(3) Master-slave experiment in free space

In this experiment, the subject wore the exoskeleton and performed various gestures in free space to observe the motion tracking the performance of the slave hand.

(4) Master-slave experiment in constrained space

In constrained space, the force reproduction performance of the master hand was verified. The master hand teleoperated the index finger to interact with a sponge ball. The contacting force can be obtained from the pressure sensor, and feedback to the master hand in real-time.

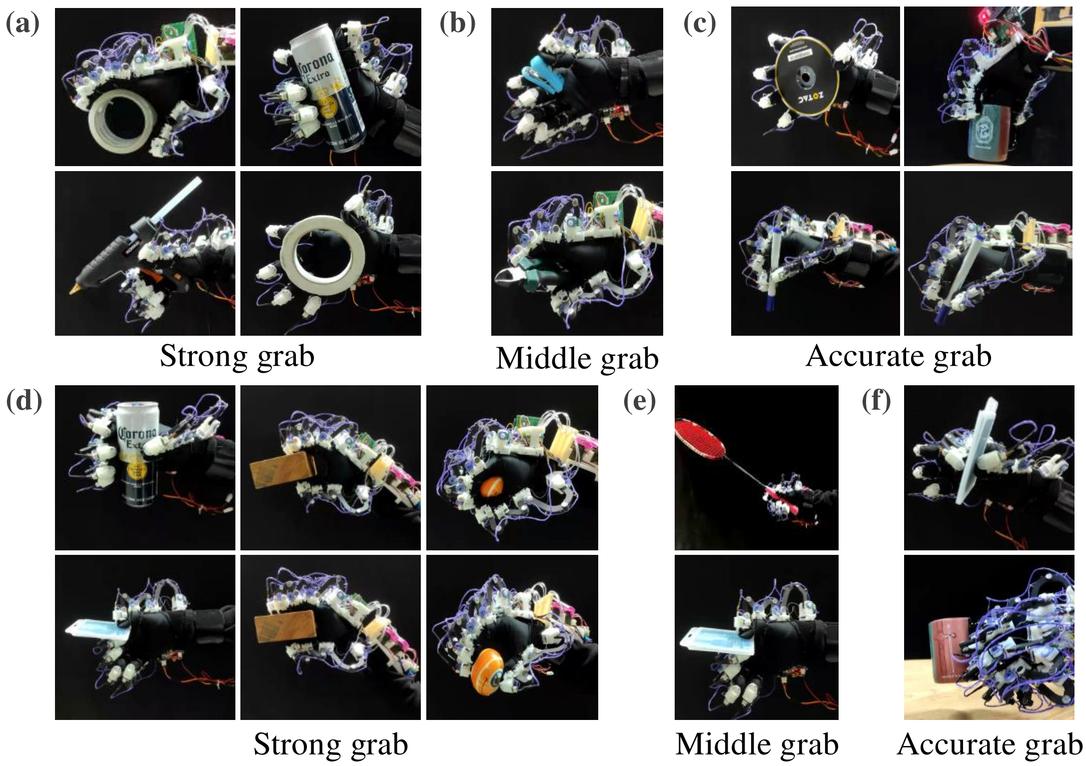

Figure. 6. Grasping verification based on Feix classification. (a) Thumb abduction motion with strong grab force. (b) Thumb abduction motion of middle grab force. (c) Thumb abduction motion of small grab force. (d) Thumb adduction motion of strong grab force. (e) Thumb adduction motion of middle grab force. (f) Thumb adduction motion of small grab force.

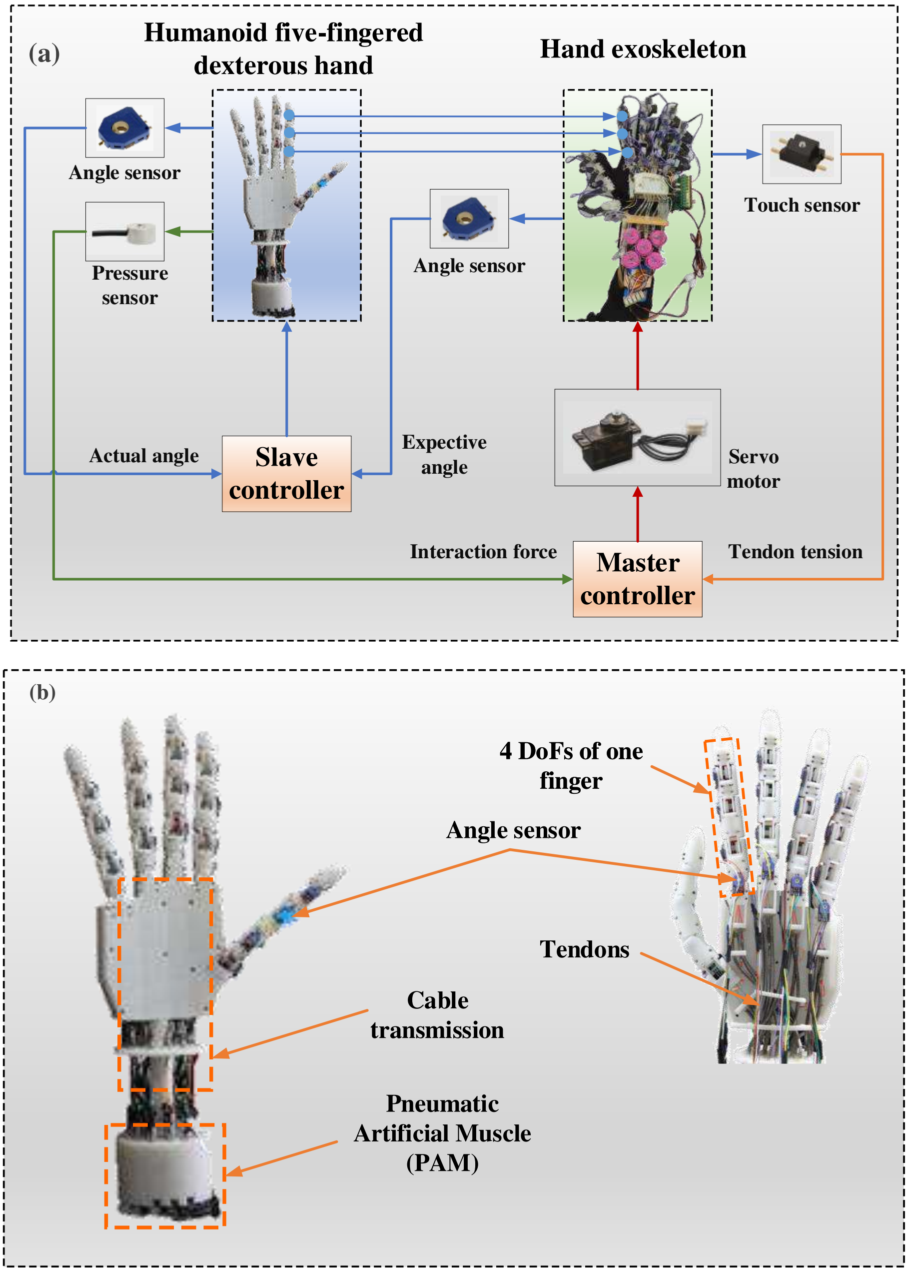

Figure 7. The experimental platform of the teleoperating system. (a) The control diagram of the teleoperating system. (b) The fully driven humanoid five-fingered dexterous slave hand.

5 Results

5.1 Accuracy of joint flexion/extension motion capture

Tables 1 and 2 show the mean values and errors of the measured angles of the index finger DIP, PIP, and MCP of the master hand under the bending state of 30° and 60°. The errors of the joint angles are all within ±3°.

5.2 Tendon tension control

Figure 8 shows the curve of the joint angle and the tension of the tendon. With the change of the index finger joint angle, the pressure data detected by the sensor exhibited a small range of fluctuations near the initial tension value. When the slave hand moved without any contact with the environment, the master hand still maintained a stable output tension at any time, which proves that the force reproduction system can achieve the desired effect.

Table 1 Joint angle test with input reference of 30°

Actual Joint Angle	DIP	PIP	MCP
The mean value	28.44°	27.02°	32.27°
Error	-1.56°	-2.98°	2.27°

Table 2 Joint angle test with input reference of 60°

Actual Joint Angle	DIP	PIP	MCP
The mean value	58.74°	62.95°	58.64°
Error	-1.26°	2.95°	-1.36°

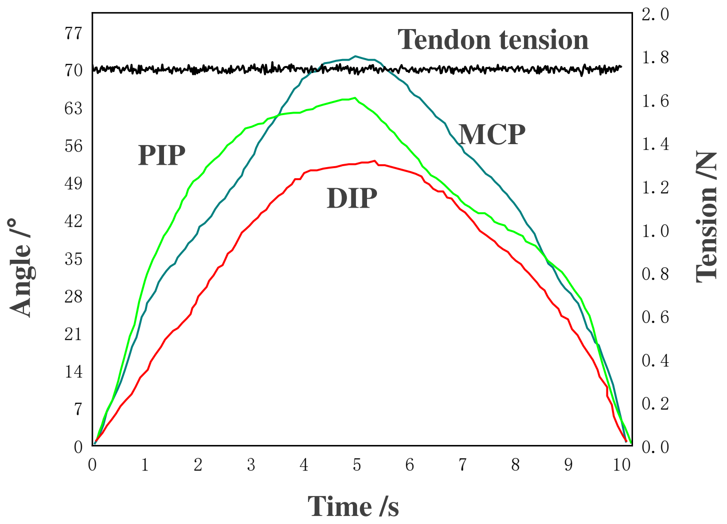

Figure 8. The experimental curve of tendon tension control.

5.3 Master-slave follow in free space

In the master-slave follow experiment in free space, the master hand changed different gestures, and the snapshots of synchronous mapping to the slave hand are shown in Figure 9. It can be seen that the gestures reproduced by the slave hand are consistent with those of the master hand.

5.4 Master-slave control in constrained space

Figure 10 shows the master-slave teleoperation in the constraint space, which is divided into five steps.

Step I: Approaching. The slave hand moved in free space and gradually approaches while not in contact with the sponge ball. At this stage, there was no contacting force on the slave hand, and the master hand only output the initial tension.

Step II: Extrusion. The slave hand started to contact the sponge ball and gradually squeezed the sponge ball. The interaction force of the slave hand gradually increased. At the same time, the tension of the tendon followed the dynamic process of the slave hand.

Step III: Holding. The slave hand continued to squeeze the sponge ball and hold it for some time. At this time, the contacting force of the slave hand and the tension of the tendon of the master hand only showed a small fluctuation.

Step IV: Releasing. The sponge ball was gradually released by the slave hand. At this time, the contacting force of the slave hand and the tension of the tendons of the master hand decreased rapidly.

Step V: Disengagement. The slave hand was completely out of contact with the sponge ball and returned to free space. At this time, the output interaction force from the hand returned to zero, and the tension of the master hand tendons was also restored to the initial tension.

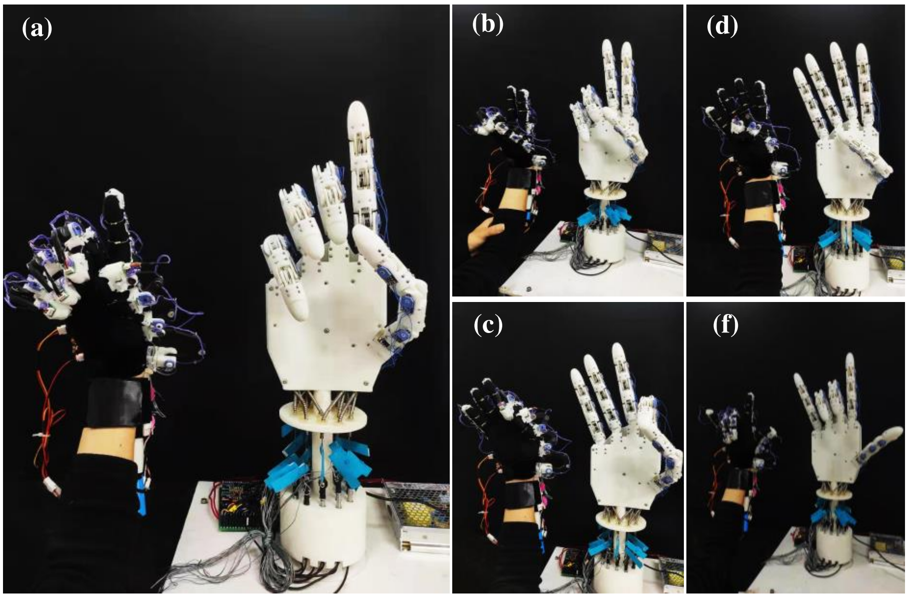

Figure 9. Master-slave mapping display in free space. (a) Gesture with single finger, (b) Two fingers, (c) Three fingers, (d) Four fingers, (e) Five fingers.

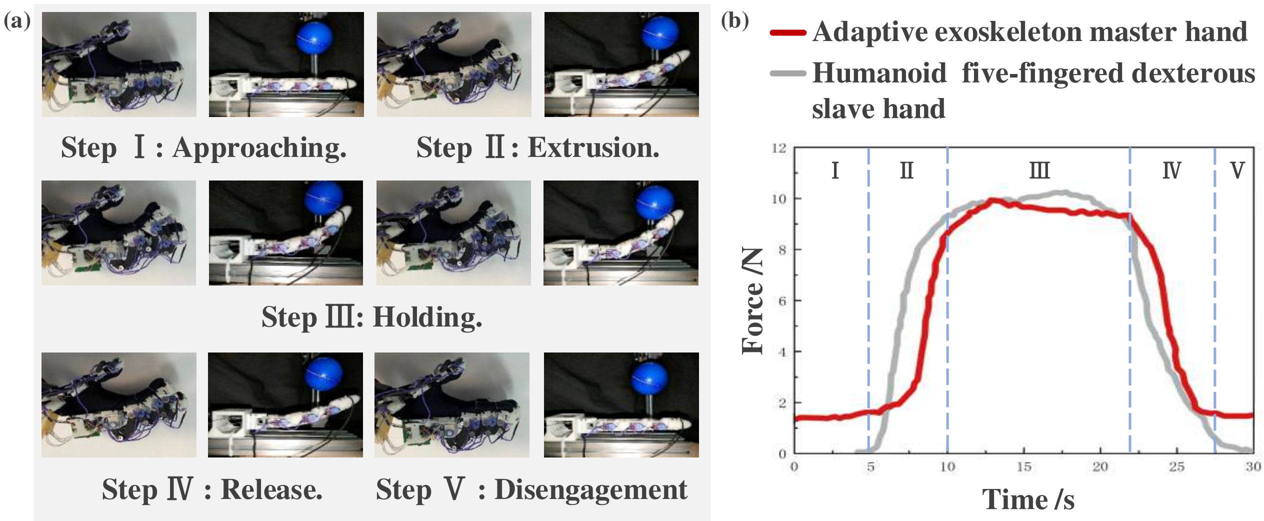

Figure 10. Master-slave interaction control experiment. (a) The experiment processes. (b) The experiment results in curves.

6 Discussion

The primary problem to be solved for the hand exoskeleton is that it cannot produce mechanical constraints to the motion of the human hand. The proposed adaptive exoskeleton master hand has 20 DoFs and covers the entire hand motion. It was observed in the motion and grasping tests that after wearing the adaptive hand exoskeleton, the subject completed different grasping actions, and all of the actions were not constrained, which proved that the hand exoskeleton could be adapted to the human hand.

Then, the master hand maps the motion of human fingers to the slave hand, and the coupled motion between the knuckles makes it challenging for the master hand to accurately obtain the angles of the finger joints. This paper proposes a novel finger exoskeleton based on the closed chain cascade structure, which constitutes an independent four-link closed-loop kinematic chain with each finger joint. The advantage of this mechanism is that each kinematic closed chain only captures the corresponding joint angle, and the accurate joint angle capture model can be established without considering the coupling motion constraints between knuckles. It can be seen from the master hand joint motion experiment that the angle capture accuracy of each joint of the master hand index finger is within $\pm 3°$ after the geometric model conversion. Such error can be considered to be acceptable.

Finally, the master hand is required to reproduce the contacting force between the slave hand and its object. This paper used the servo motor as the driving source for each finger exoskeleton and changed the length of the tendon to control its tension. The detection unit was integrated at each fingertip to detect the tension of the tendon, which controlled the output of the drive unit instantaneously. To ensure the response speed of the master hand, an initial tension was preset. In the verification of the tension control experiment, with the change of the angle of the finger joints, the output tension value of the master hand was kept steady. In the master-slave interaction experiment in constrained space, we found that in the extrusion stage, with the increase of the interaction force, the deviation between the angle of the master hand joint and the slave hand joint angle increases gradually, because the slave hand moves restricted immediately after touching the sponge ball. The slave hand fed back the interactive force to the master hand, and the fingers further squeezed the sponge ball after sensing the contacting event. At this time, the joint angle of the master hand still increased, while the joint angle of the slave hand tends to be stable. In the holding stage, the tension of the tendon of the master hand and the contacting force of the slave hand fluctuated slightly. This is because the fingers of the master hand are required to resist the contraction of the tendon to keep the joint posture unchanged. Thus, both the master and slave controllers are constantly adjusted to adapt to the motion of the fingers.

The adaptive hand exoskeleton proposed in this paper meets the requirements of teleoperation for the master hand. However, there are still some issues to be further studied and improved in future work. First, the hand exoskeleton only consists of the front four DoFs of each finger and does not consider the CMC joint. A new mechanism with the CMC joint will be more compliant with the movement of the human hand. Second, the hand exoskeleton in this paper only reproduces the force sensing at the finger end, and the human hand cannot accurately perceive the force from the knuckles of the hand, which is not conducive to the operator making correct decisions. In the future, we will optimize the sensor and fully reproduce the interactive information from hands.

7 Conclusion

It is of great importance to have a dexterous slave hand with diverse operation capabilities in remote operation tasks, such as screwing, pushing, pulling, and pressing, which requires a master hand to capture the motion of the human hand without any mechanical constraints and reproduce the force from slave hand in real-time.

This paper proposes a novel finger exoskeleton configuration composed of a cascade of four-link closed-loop kinematic chains. Based on this mechanism, an adaptive hand exoskeleton, which possesses 20 joint DoFs, is developed. The tension control of the tendon through the servo motor allows the master hand to achieve force reproduction from the slave hand. A series of hand exoskeleton performance tests and master-slave interaction experiments in free and constrained space were carried out. The experimental results show that the adaptive hand exoskeleton satisfies wearable adaptability, which can remotely control the slave hand to follow various gestures from the master hand, and the joint motion capture is stable and reliable. It is comparatively accurate to reproduce the interaction force between the slave and its objects.

Availability of data and materials

Not applicable.

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Not applicable.

Authors’ contributions

WW wrote the draft manuscript and conceived of the presented idea; BZ and MD conducted experiments; BF, GB, and SC were in charge of the whole trial. All authors read and approved the final manuscript.

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Competing interests

The authors declare no competing financial interests.

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